# PDF4LHC2021

## Benchmarking of CT18, MSHT20, NNPDF3.1 global PDF fits

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On behalf of PDF4LHC21 Combination Group

Snowmass Energy Frontier Workshop

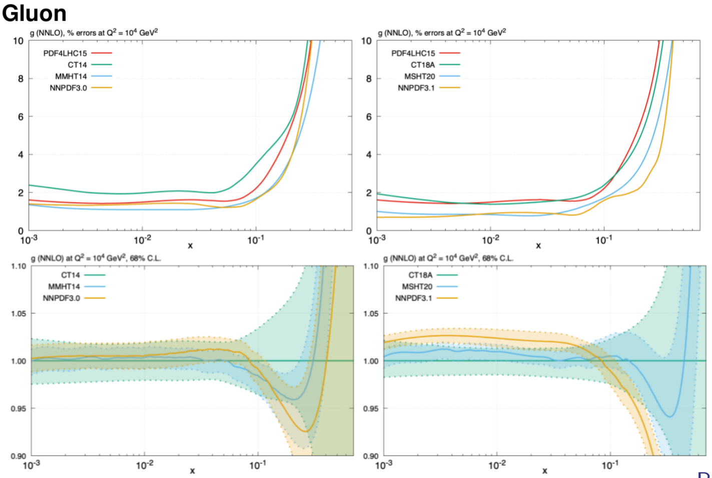
More information in recent update article: TC arXiv:2108.09099.

# Introduction - PDF Landscape

- PDF4LHC15 was a 1 year benchmarking exercise of the CT14, MMHT14, NNPDF3.0 PDFs which resulted in a combination set.
- It has now been more than 5 years since the PDF4LHC15 benchmarking exercise.
- Increasing amounts of data coming out of the LHC, greater precision, more channels, more differential $\Rightarrow$ changes in PDFs.
- Many theoretical improvements $\Rightarrow$ full NNLO predictions, methodological improvements (parameterisations, algorithms, etc).
- PDFs now known more accurately and precisely than ever before, but some differences emerging $\Rightarrow$ benchmarking needed.
- We consider 3 global PDF fits most recent sets, which include much of the recent datasets: MSHT20, CT18, NNPDF3.1.

Work undertaken through many useful discussions, many thanks to all members involved.

# Introduction - Changes in PDFs



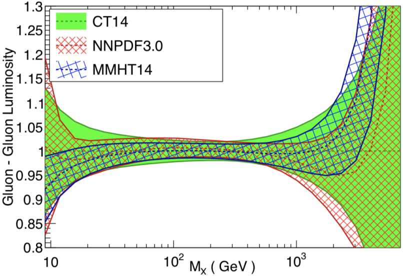

- Reduction in PDF uncertainties seen across all 3 groups.
- Central value agreement not as good, some differences emerging.

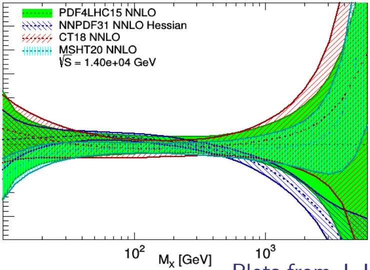
Plots from L. Harland-Lang

Note: CT18A shown for ease of comparison, however CT18 is the default set.

# Introduction - Changes in PDFs

N.B. Different baseline for ratio in two plots and different colours.




Plots from J. Huston

- Central value spread effects gluon-gluon luminosity.
- If these were to be combined à la PDF4LHC15, there will be some contribution to uncertainty from spread as well as the uncertainties.
- Motivates understanding these differences and their origin $\Rightarrow$ PDF4LHC21 benchmarking.
- New PDFs CT18, MSHT20, NNPDF3.1 $\Rightarrow$ now is a good time to undertake a benchmarking exercise, ahead of new $\Rightarrow$ PDF4LHC21 combination - feedback on what is ultimately provided is welcome!

# PDF Benchmarking: Aim and Approach

- Desire to understand origin of differences:
  - Are they due to variations of experimental input, different theory settings, methodologies? Are these equally valid choices?
- Seek to remove as many differences in input/approach as possible:
  - Common input data - Small subset of datasets $\Rightarrow$ reduced fits.
  - Common theory settings wherever possible.
  - Examine methodological differences in parallel as much as possible.
- Reduced fits offer *ease of comparison at expense of robustness*.
- To benchmark the reduced fits:
  - Compare PDFs directly to look for areas of difference.
  - Compare $\chi^2$ to determine particular datasets showing differences.
  - Compare cross-sections and point-by-point theory predictions.
- Once differences in reduced fits understood, slowly add datasets moving towards global fits, focusing on key areas of differences.
- End result: PDF4LHC21 set of PDFs, central PDFs and Hessian error set (30-50 sufficient) representing the 3 published PDFs.

# PDF Benchmarking: Datasets

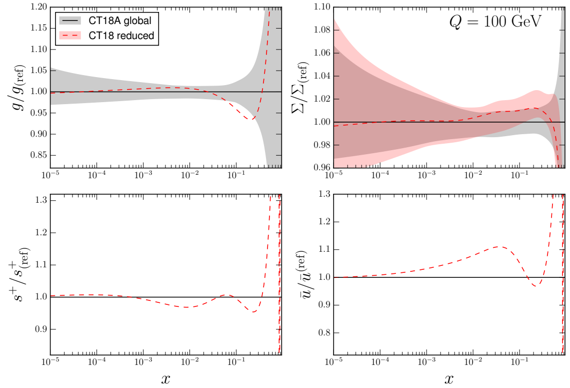
- Chosen subset of datasets fit by all 3 groups in (almost) the same way, list is surprisingly small! Small reduced fit set.
- Take most conservative cuts applied by any group for consistency.
- Ensure enough datasets and a sufficient variety of dataset types are fit to have some (but incomplete) constraints on all PDF flavours.
- Overall list:
  - NMC deuteron to proton ratio in DIS.
  - NuTeV dimuon cross-sections.
  - HERA I+II inclusive cross-sections from DIS.
  - E866 fixed target Drell-Yan ratio $pd/pp$ data.
  - D0 $Z$ rapidity distribution.
  - ATLAS $W, Z$ 7 TeV rapidity distribution, only $Z$ peak and central.
  - CMS 7 TeV $W$ asymmetry.
  - CMS 8 TeV inclusive jet data.
  - LHCb 7, 8 TeV $W, Z$ rapidity distributions.
  - BCDMS proton and deuteron DIS data.

# PDF Benchmarking: Theory Settings

- Choose common theory settings for simplicity:
  - Same heavy quark masses ($m_c = 1.4$GeV, $m_b = 4.75$GeV) and $\alpha_S(M_Z^2) = 0.118$.
  - No strangeness asymmetry at input scale: $(s - \bar{s})(Q_0) = 0$.
  - Perturbative charm.
  - Positive definite quark distributions (lack of constraint may allow negative fluctuations).
  - No deuteron or nuclear corrections.
  - Fixed branching ratio for charm hadrons to muons.
  - NNLO corrections for dimuon data.
- Note: These are not the chosen settings for any one group, but rather are a compromise to the least common denominator in each case, *we would not recommend them for a full global fit*.

# Reduced Fits: CT18 reduced fit vs CT18A global fit

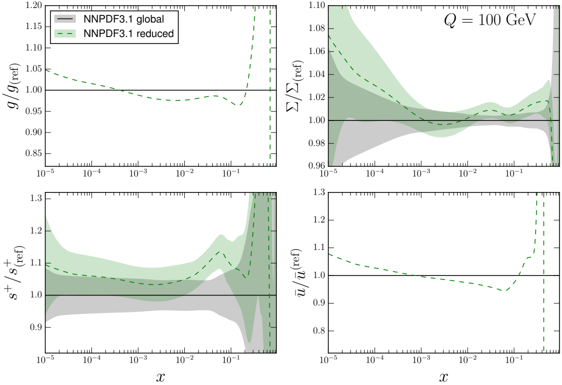
- Current Status:




- Good compatibility with change in high $x$ gluon shape and some increase in $\bar{u}$. Some changes in flavour decomposition.
- Some increase in *nominal* PDF uncertainties, particularly at low $x$.

# Reduced Fits: NNPDF reduced fit vs NNPDF3.1 global

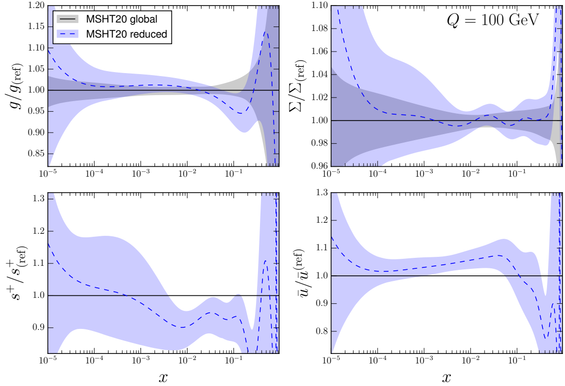
- Current Status:




- Good compatibility, changes in strangeness (see later) and change in large $x$ gluon (removal of top data, addition of CMS 8 TeV jet).
- Generally slightly increased uncertainties, particularly for the gluon.

# Reduced Fits: MSHT reduced fit vs MSHT20 global fit

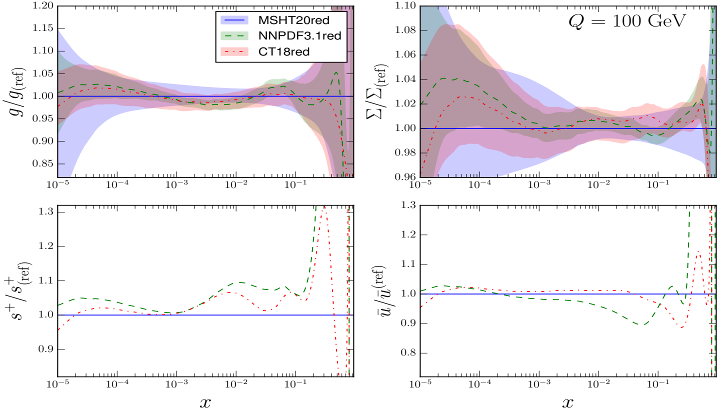
- Current Status:




- Good compatibility, changes in strangeness (removal of 8 TeV ATLAS $W, Z$ data), flavour decomposition and large $x$ gluon.
- General marked increase in uncertainties of reduced fit, particularly outside of regions where there are data.

# Reduced Fits PDF Comparison - central values

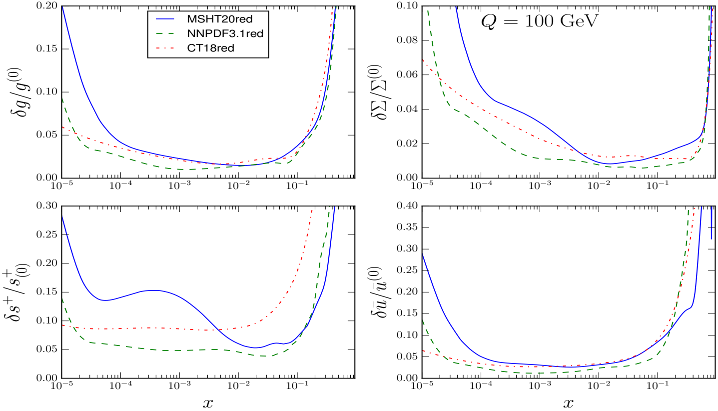
- Current Status:




- Good general agreement within uncertainties, perhaps with the exception of high $x$ flavour decomposition of NNPDF.
- Nonetheless, strangeness and flavour decomposition improved through benchmarking (NuTeV - later). *Note this is without the $t\bar{t}$ added.

# Reduced Fits PDF Comparison - uncertainties

- Current Status:




- Similar size uncertainties in data regions, MSHT generally larger errors where constraints lacking in reduced fit.
- Parallel study into differences in uncertainty bands ongoing.

*Note this is without the $t\bar{t}$ added.

# Reduced Fits Datasets $\chi^2$ Comparison

| ID | Expt. | $N_{pts}$ | $\chi^2/N_{pts}$ (CT) | $\chi^2/N_{pts}$ (MSHT) | $\chi^2/N_{pts}$ (NNPDF) |
|---|---|---|---|---|---|
| 101 | BCDMS $F_2^p$ | $329/163^{\dagger\dagger}/325^{\dagger}$ | 1.06 | 1.00 | 1.21 |
| 102 | BCDMS $F_2^d$ | $246/151^{\dagger\dagger}/244^{\dagger}$ | 1.06 | 0.88 | 1.10 |
| 104 | NMC $F_2^d/F_2^p$ | $118/117^{\dagger}$ | 0.93 | 0.93 | 0.90 |
| 124+125 | NuTeV $\nu\mu\mu + \bar{\nu}\mu\mu$ | 38+33 | 0.79 | 0.83 | 1.22 |
| 160 | HERAI+II | 1120 | 1.23 | 1.20 | 1.22 |
| 203 | E866 $\sigma_{pd}/(2\sigma_{pp})$ | 15 | 1.24 | 0.80 | 0.43 |
| 245+250 | LHCb 7TeV & 8TeV $W,Z$ | 29+30 | 1.15 | 1.17 | 1.44 |
| 246 | LHCb 8TeV $Z \to ee$ | 17 | 1.35 | 1.43 | 1.57 |
| 248 | ATLAS 7TeV $W,Z$(2016) | 34 | 1.96 | 1.79 | 2.33 |
| 260 | D0 Z rapidity | 28 | 0.56 | 0.58 | 0.62 |
| 267 | CMS 7TeV electron $A_{ch}$ | 11 | 1.47 | 1.52 | 0.76 |
| 269 | ATLAS 7TeV $W,Z$(2011) | 30 | 1.03 | 0.93 | 1.01 |
| 545 | CMS 8TeV incl. jet | $185/174^{\dagger\dagger}$ | 1.03 | 1.39 | 1.30 |
| Total | $N_{pts}$ | — | 2263 | 1991 | 2256 |
| Total | $\chi^2/N_{pts}$ | — | 1.14 | 1.15 | 1.20 |

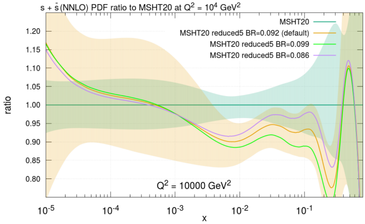
PDF4LHC21 reduced fit dataset $\chi^2/N_{pts}$ after fitting, $^{\dagger\dagger}$MSHT $^{\dagger}$NNPDF.

- Similar overall quality of fit in $\chi^2/N$.
- Differences remaining in some datasets:
  - NuTeV agreement improved but difference remains, seen in $s + \bar{s}$.
  - Some differences in NNPDF fit quality to small datasets, e.g. CMS 7 TeV electron asymmetry.

Table from T. Hobbs

# Flavour Decomposition - Strangeness and NuTeV

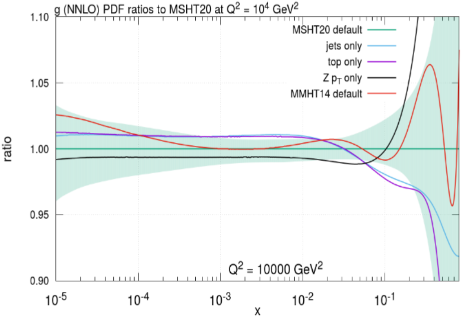
- One of the main differences between the first reduced sets was in the flavour decomposition and strangeness.
- NuTeV dimuon data key driver of this, complicated dataset:
  - Requires knowledge of charm hadron $\to$ muon branching ratio (BR).
  - Non-isoscalar nature of target.
  - Prefers non-zero strangeness asymmetry.
  - Acceptance corrections required.
- BR($c \to \mu$) anti-correlated with strangeness, 3 groups have different values:
  - NNPDF $0.087 \pm 0.005$
  - MSHT $0.092 \pm 0.01$ variable.
  - CT 0.099, normalisation uncertainty.




- Choose same BR fixed at 0.092 $\Rightarrow$ better strangeness agreement, largely within uncertainties between all 3 groups.
- Also aids reduction in flavour decomposition differences.

# High $x$ gluon

- High $x$ gluon of interest to both reduced and global fits.
- 3 main datasets play a role here - jet data, top data, $Zp_T$ data, different pulls:
- Not straightforward to fit some of them:
  - Difficulties fitting all bins.
  - Possible tensions.
  - Issue of correlated systematics.




- Global fit is a balance between these different pulls.
- MSHT, CT, NNPDF observe differences in the relative importance of these datasets and the quality of their individual fits
  - *does the same hold in reduced fits and can we understand this better in this context?*

# ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets

- Comes differential in 4 variables with correlations - $m_{tt}, y_t, y_{tt}, p_t^T$.
- MSHT*, CT+ difficulties fitting all 4 distributions simultaneously.
- MSHT, CT, ATLAS− cannot get good fit to $y_t$ or $y_{tt}$ individually.
- NNPDF3.0 however able to fit all 4 distributions well individually†.

## Benchmarking:

- Adding to reduced fit, what happens?

| Distribution/N | $p_t^T/8$ | $y_t/5$ | $y_{tt}/5$ | $m_{tt}/7$ | Total |
|---|---|---|---|---|---|
| MSHT PDF4LHC15 in | 3.0 | 10.6 | 17.6 | 4.3 | 35.5 |
| NNPDF PDF4LHC15 in | 3.4 | 9.5 | 16.2 | 4.1 | 33.2 |
| CT PDF4LHC15 in | 3.1 | 10.1 | 15.3 | 4.2 | 32.7 |
| MSHT fit uncorrelated | 3.8 | 8.4 | 12.5 | 6.4 | 31.2 |
| CT fit uncorrelated | 3.4 | 12.9 | 17.3 | 6.1 | 39.7 |
| NNPDF fit uncorrelated | 7.2 | 3.9 | 5.1 | 2.5 | 18.7 |
| MSHT fit correlated | - | - | - | - | 130.6 |
| NNPDF fit correlated | - | - | - | - | 122.7 |
| MSHT fit decorrelated | - | - | - | - | 35.3 |

**Before Fitting**

All groups $\chi^2$ in agreement, same pattern - poor $\chi^2$ for rapidity data

**After Fitting**

MSHT and CT see poor fits to rapidities $y_t$, $y_{tt}$, as in global fits

**After Fitting**

NNPDF see good fits to rapidities $y_t$, $y_{tt}$, as in global fits.

- Same behaviour as in global fits after fitting....

See top discussion session tomorrow for more details, e.g. Thorne.

* S. Bailey & L.Harland-Lang 1909.10541.
† Czakon et al 1611.08609.
+ Kadir et al 2003.13740.
− ATL-PHYS-PUB-2018-017.

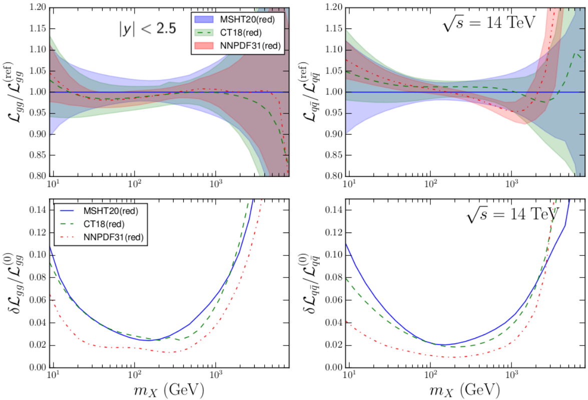
# Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

- How can we explain these differences in global and reduced fits?
- Global fits have different fit environments - different weights and other datasets included, tensions may affect fit quality for this dataset:
  - NNPDF3.0 had little jet data - perhaps tensions cause issues in $y_t$, $y_{tt}$. NNPDF4.0 seeing similar behaviour to other groups.
  - NNPDF reduced fit up-weights this dataset by putting all data in training (as small dataset) - perhaps up-weighting causes difference.
- Investigate weights and tensions in reduced fit environment:

| Dataset (N) | MSHT reduced (default CMS8j) | NNPDF reduced (default CMS8j) | MSHT reduced (CMS7j) | MSHT reduced (AT7j) | MSHT reduced (no jets) | MSHT reduced (CMS8j, double weight $t\bar{t}$) |
|---|---|---|---|---|---|---|
| $\chi^2/N$ | 1.15 | 1.20 | 1.11 | 1.17 | 1.12 | 1.15 |
| $p_t^T$ (8) | 3.8 | 7.2 | 4.0 | 4.6 | 4.5 | 4.2 |
| $y_t$ (5) | 8.4 | 4.3 | 6.4 | 5.5 | 5.2 | 5.8 |
| $y_{tt}$ (5) | 12.5 | 5.7 | 7.2 | 5.2 | 6.6 | 7.4 |
| $m_{tt}$ (7) | 6.4 | 2.4 | 6.4 | 6.4 | 7.4 | 6.5 |
| $t\bar{t}$ total | 31.2 | 19.6 | 24.0 | 21.6 | 23.8 | 23.9 |

- Weights and tensions with other datasets notably affect fit quality, removing these differences $\Rightarrow$ similar behaviour can be observed.

# Reduced Fits: Current Status Summary*




- Very good agreement in gluon-gluon, quark-antiquark, quark-quark and quark-gluon luminosities. (Latter two in backup slides).
- Same data and theory settings $\rightarrow$ consistent PDFs. Reduced fits well understood, benchmarking successful!

*Note this is without the $t\bar{t}$ added.

# Conclusions and Future Work

- New data, theoretical improvements, PDF methodological improvements have meant substantial changes since PDF4LHC15.
- We are performing a benchmarking exercise of the 3 global fit PDF groups most recent sets: MSHT20, CT18, NNPDF3.1.
- Based on comparing "Reduced Fits" ⇒ very good consistency is now observed between the three groups, particularly in luminosities.
- Overall very good progress towards benchmarking the global fits.
- End result: PDF4LHC21 set of PDFs, central PDFs and Hessian error set (30-50 sufficient) representing the 3 published PDFs.
- Are there any lessons from PDF4LHC15 we can take into account?

Many thanks to all those involved in this work/discussions, special thanks to T. Hobbs, T.-J. Hou, L. Harland-Lang, P. Nadolsky, E. Nocera, J. Rojo, R. Thorne for providing tables/plots/fits.

# Backup Slides

# Introduction - New Datasets (MSHT20)

LHCb $W, Z$ data at high rapidity

CMS W+c

Precision DY data

⇒ Flavour Decomposition

LHC Jet, $Zp_T$, $t\bar{t}$ data

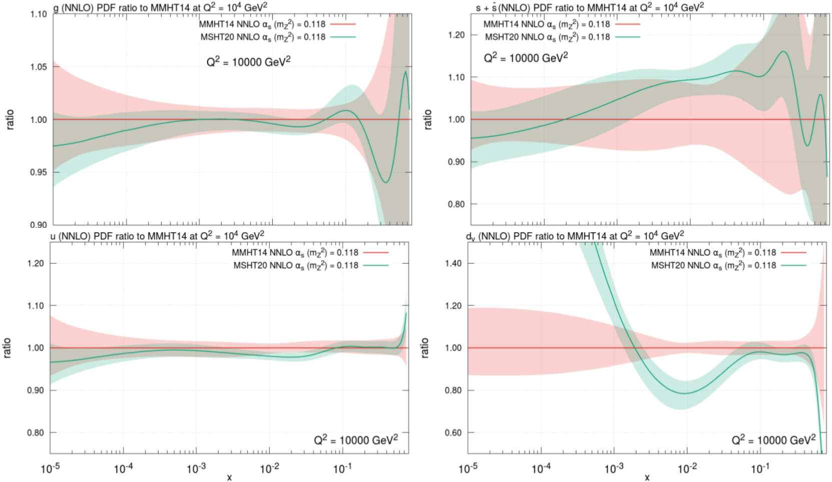
⇒ High $x$ gluon

| Data set | Points | NLO $\chi^2/N_{pts}$ | NNLO $\chi^2/N_{pts}$ |
|---|---|---|---|
| DØ $W$ asymmetry | 14 | 0.94 (2.53) | 0.86 (14.7) |
| $\sigma_{t\bar{t}}$ [93]- [94] | 17 | 1.34 (1.39) | 0.85 (0.87) |
| LHCb 7+8 TeV $W+Z$ [95, 96] | 67 | 1.71 (2.35) | 1.48 (1.55) |
| LHCb 8 TeV $Z \to ee$ [97] | 17 | 2.29 (2.89) | 1.54 (1.78) |
| CMS 8 TeV $W$ [98] | 22 | 1.05 (1.79) | 0.58 (1.30) |
| CMS 7 TeV $W+c$ [99] | 10 | 0.82 (0.85) | 0.86 (0.84) |
| ATLAS 7 TeV jets $R = 0.6$ [18] | 140 | 1.62 (1.59) | 1.59 (1.68) |
| ATLAS 7 TeV $W+Z$ [20] | 61 | 5.00 (7.62) | 1.91 (5.58) |
| CMS 7 TeV jets $R = 0.7$ [100] | 158 | 1.27 (1.32) | 1.11 (1.17) |
| ATLAS 8 TeV $Z$ $p_T$ [75] | 104 | 2.26 (2.31) | 1.81 (1.59) |
| CMS 8 TeV jets $R = 0.7$ [101] | 174 | 1.64 (1.73) | 1.50 (1.59) |
| ATLAS 8 TeV $t\bar{t} \to l + j$ sd [102] | 25 | 1.56 (1.50) | 1.02 (1.15) |
| ATLAS 8 TeV $t\bar{t} \to l^+l^-$ sd [103] | 5 | 0.94 (0.82) | 0.68 (1.11) |
| ATLAS 8 TeV high-mass DY [73] | 48 | 1.79 (1.99) | 1.18 (1.26) |
| ATLAS 8 TeV $W^+W^-$+ jets [104] | 30 | 1.13 (1.13) | 0.60 (0.57) |
| CMS 8 TeV $(d\sigma_{t\bar{t}}/dp_{T,t}dy_t)/\sigma_{t\bar{t}}$ [105] | 15 | 2.19 (2.20) | 1.50 (1.48) |
| ATLAS 8 TeV $W^+W^-$ [106] | 22 | 3.85 (13.9) | 2.61 (5.25) |
| CMS 2.76 TeV jets [107] | 81 | 1.53 (1.59) | 1.27 (1.39) |
| CMS 8 TeV $\sigma_{t\bar{t}}/dy_t$ [108] | 9 | 1.43 (1.02) | 1.47 (2.14) |
| ATLAS 8 TeV double differential $Z$ [74] | 59 | 2.67 (3.26) | 1.45 (5.16) |
| Total, LHC data in MSHT20 | 1328 | 1.79 (2.18) | 1.33 (1.77) |
| Total, non-LHC data in MSHT20 | 3035 | 1.13 (1.18) | 1.10 (1.18) |
| Total, all data | 4363 | 1.33 (1.48) | 1.17 (1.36) |

- Lots of new information constraining PDFs.

MSHT20, 2012.04684

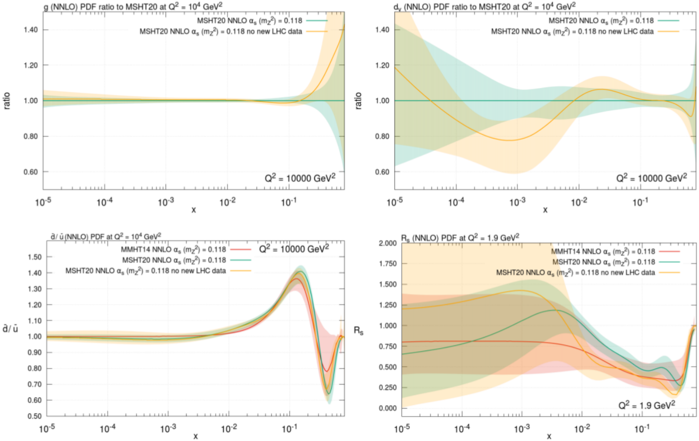
# Introduction - Changes in PDFs: MSHT20




- Notable changes in strangeness (ATLAS $W, Z$ data), down valence (new data and parameterisation), gluon (new jets, top, $Zp_T$ data).

More details in R. Thorne's MSHT20 talk.

# Effect of new LHC data in MSHT20

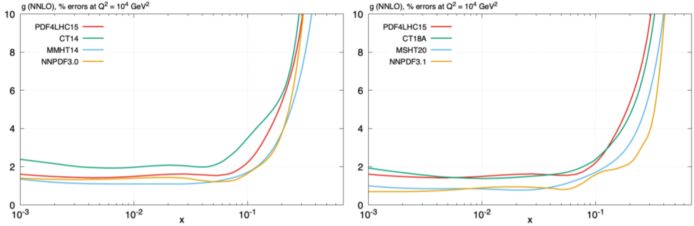



Main effect on details of flavour, i.e. $d_V$ shape, increase in strange quark for $0.001 < x < 0.3$ and $\bar{d}, \bar{u}$ details, though also partially from parameterisation change. Decrease in high-$x$ gluon.

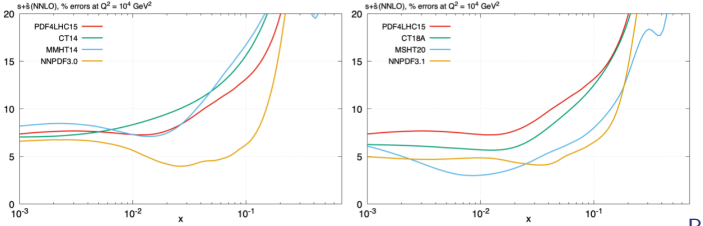
*MSHT20 2012.04684. Slide from R. Thorne

# Introduction - Changes in PDFs: Uncertainties

## Gluon




## Strange



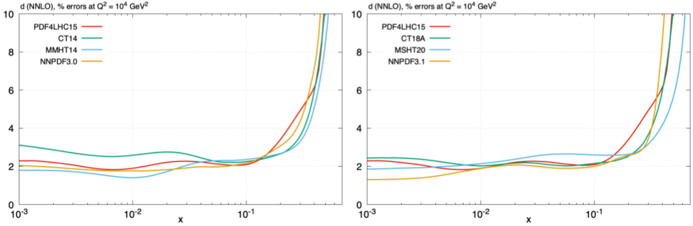

- Reduction in PDF uncertainties seen across all 3 groups.

Plots from L. Harland-Lang

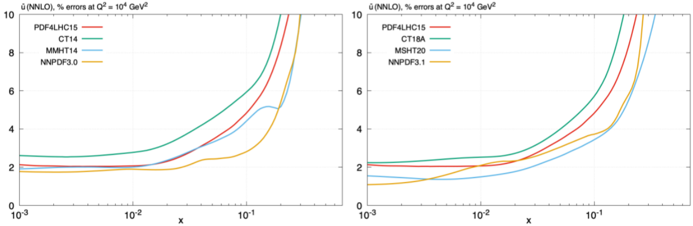
Note: CT18A shown for ease of comparison, however CT18 is the default set.

# Introduction - Changes in PDFs: Uncertainties

**Down**




**Anti-up**




- Reduction in PDF uncertainties seen across all 3 groups.

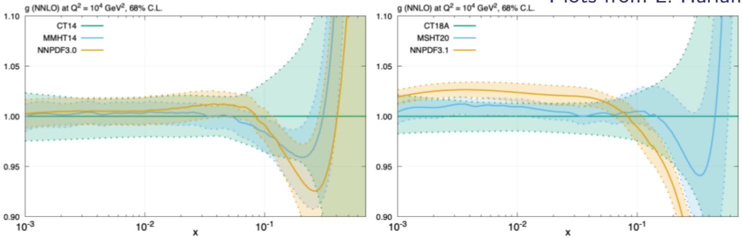
Plots from L. Harland-Lang

Note: CT18A shown for ease of comparison, however CT18 is the default set.

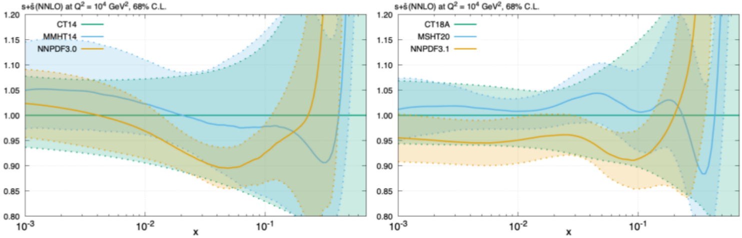
# Introduction - Changes in PDFs: Central Values

## Gluon

Plots from L. Harland-Lang



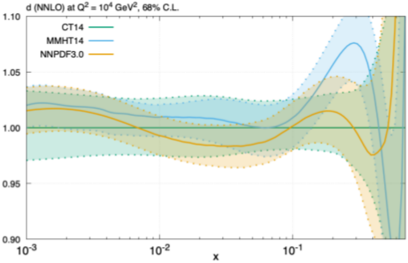

## Strange

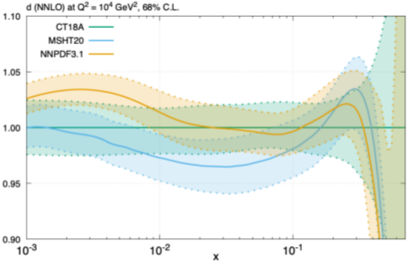



- Central value agreement not as good, some differences emerging.

# Introduction - Changes in PDFs: Central Values

**Down**



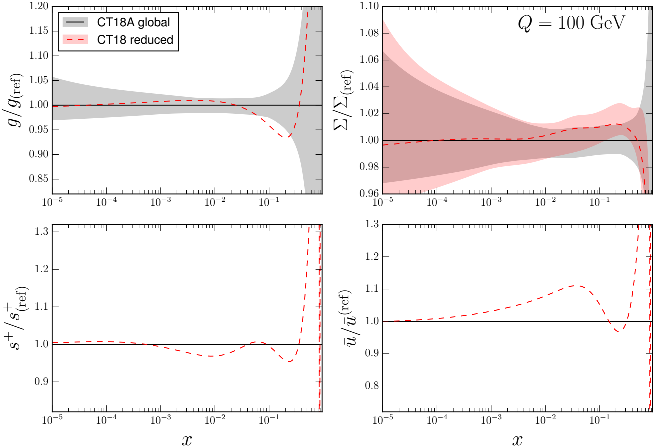

- Central value agreement not as good, some differences emerging.
- In summary:
  - Large amount of progress since the last PDF4LHC combination on experimental, theoretical and methodological fronts.
  - Some differences emerging between the 3 sets.

$\Rightarrow$ now is a good time to undertake a benchmarking exercise ahead of a new PDF4LHC future combination.

Plots from L. Harland-Lang

# Reduced Fits: CT18 changes - central values

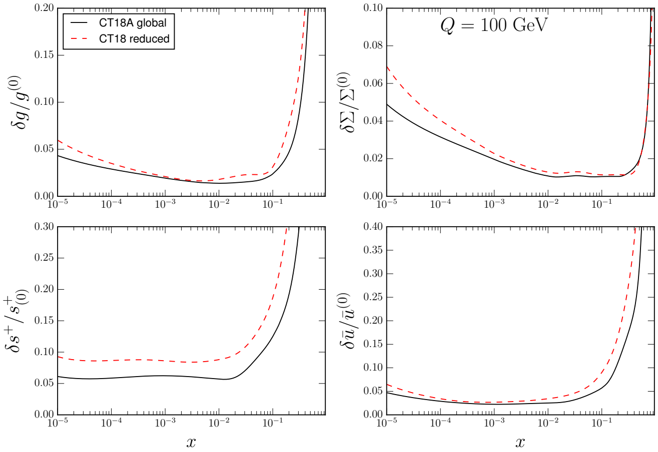
- Current Status:




- Good compatibility with change in high $x$ gluon shape and some increase in $\bar{u}$. Some changes in flavour decomposition.

# Reduced Fits: CT18 changes - uncertainties

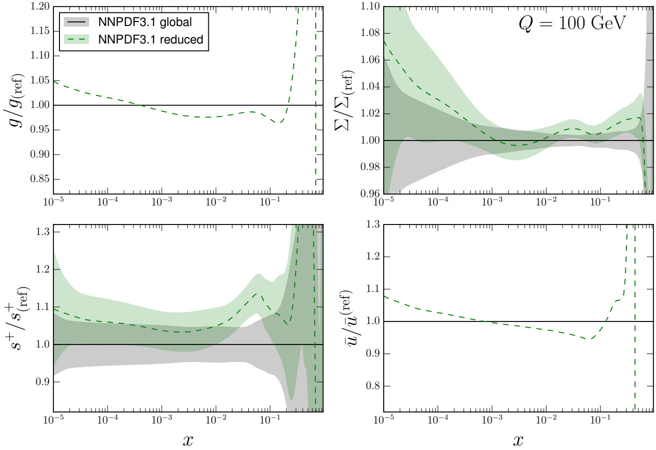
- Current Status:




- Some increase in *nominal* PDF uncertainties, particularly at low $x$.

# Reduced Fits: NNPDF3.1 changes - central values

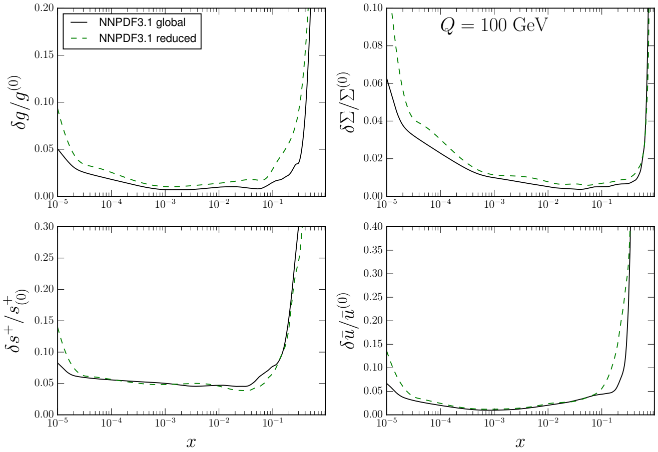
- Current Status:




- Good compatibility, changes in strangeness (see later) and change in large $x$ gluon (removal of top data, addition of CMS 8 TeV jet).

# Reduced Fits: NNPDF3.1 changes - uncertainties

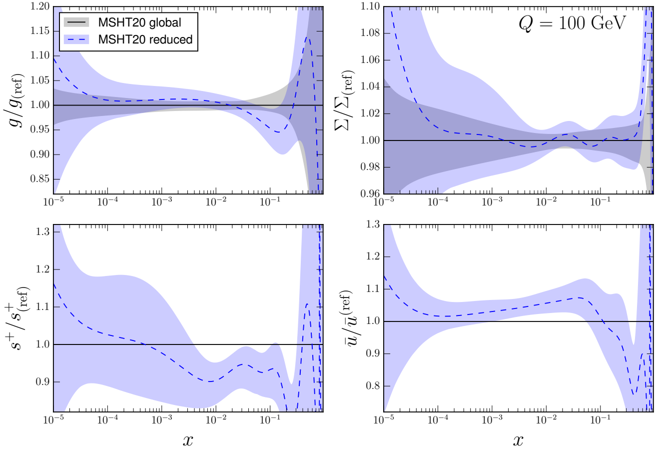
- Current Status:




- Generally slightly increased uncertainties, particularly for the gluon.

# Reduced Fits: MSHT20 changes - central values

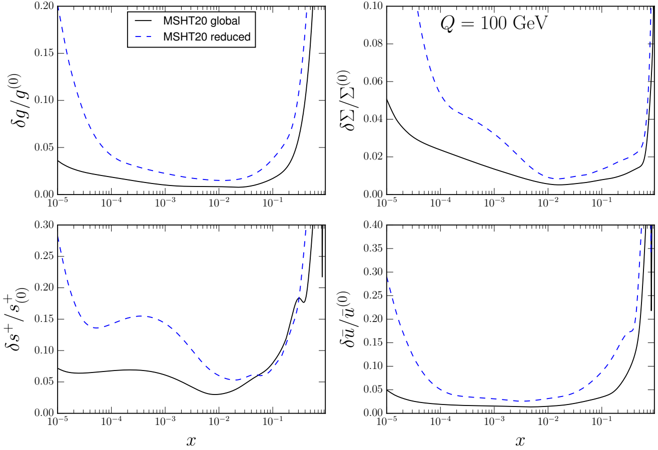
- Current Status:




- Good compatibility, changes in strangeness (removal of 8 TeV ATLAS $W, Z$ data), flavour decomposition and large $x$ gluon.

# Reduced Fits: MSHT20 changes - uncertainties

- Current Status:




- General marked increase in uncertainties of reduced fit, particularly outside of regions where there are data.

# PDF4LHC15 in Predictions Datasets $\chi^2$ Comparison

- First make predictions with PDF4LHC15 PDFs, identifies any differences in theory/data between groups with fixed PDFs.
- Current status:

Table from T. Hobbs

| ID | Expt. | $N_{pt}$ | $\chi^2/N_{pt}$ (CT) | $\chi^2/N_{pt}$ (MSHT) | $\chi^2/N_{pt}$ (NNPDF) |
|---|---|---|---|---|---|
| 101 | BCDMS $F_2^p$ | $329/163^{\dagger\dagger}/325^{\dagger}$ | 1.35 | 1.2 | 1.51 |
| 102 | BCDMS $F_2^d$ | $246/151^{\dagger\dagger}/244^{\dagger}$ | 0.97 | 1.27 | 1.24 |
| 104 | NMC $F_2^d/F_2^p$ | $118/117^{\dagger}$ | 0.92 | 0.93 | 0.94 |
| 124+125 | NuTeV $\nu\mu\mu + \bar{\nu}\mu\mu$ | 38+33 | 0.75 | 0.73 | 0.84 |
| 160 | HERAI+II | 1120 | 1.27 | 1.24 | 1.74 |
| 203 | E866 $\sigma_{pd}/(2\sigma_{pp})$ | 15 | 0.45 | 0.54 | 0.59 |
| 245+250 | LHCb 7TeV& 8TeV $W$,$Z$ | 29+30 | 1.5 | 1.34 | 1.76 |
| 246 | LHCb 8TeV $Z \to ee$ | 17 | 1.35 | 1.65 | 1.25 |
| 248 | ATLAS 7TeV $W$,$Z$(2016) | 34 | 6.71 | 7.46 | 6.51 |
| 260 | D0 Z rapidity | 28 | 0.61 | 0.58 | 0.61 |
| 267 | CMS 7TeV eletron $A_{ch}$ | 11 | 0.45 | 0.5 | 0.73 |
| 269 | ATLAS 7TeV $W$,$Z$(2011) | 30 | 1.21 | 1.23 | 1.31 |
| 545 | CMS 8TeV incl. jet | $185/174^{\dagger\dagger}$ | 1.53 | 1.89 | 1.78 |
| Total | $N_{pt}$ | — | 2263 | 1991 | 2256 |
| Total | $\chi^2/N_{pt}$ | — | 1.31 | 1.36 | 1.62 |

- Similar overall quality of fit for MSHT and CT in $\chi^2/N$, NNPDF significantly larger $\chi^2/N$.
- Differences in some datasets:
  - Difference in NNPDF HERA $\chi^2$ - flavour scheme, disappears in fit.

# Reduced Fits Datasets $\chi^2$ Comparison

- Current status:

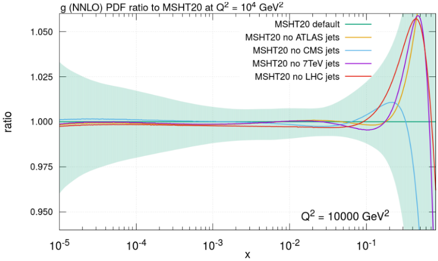
| ID | Expt. | $N_{pt}$ | $\chi^2/N_{pt}$ (CT) | $\chi^2/N_{pt}$ (MSHT) | $\chi^2/N_{pt}$ (NNPDF) |
|---|---|---|---|---|---|
| 101 | BCDMS $F_2^p$ | $329/163^{\dagger\dagger}/325^{\dagger}$ | 1.06 | 1.00 | 1.21 |
| 102 | BCDMS $F_2^d$ | $246/151^{\dagger\dagger}/244^{\dagger}$ | 1.06 | 0.88 | 1.10 |
| 104 | NMC $F_2^d/F_2^p$ | $118/117^{\dagger}$ | 0.93 | 0.93 | 0.90 |
| 124+125 | NuTeV $\nu\mu\mu + \bar{\nu}\mu\mu$ | 38+33 | 0.79 | 0.83 | 1.22 |
| 160 | HERAI+II | 1120 | 1.23 | 1.20 | 1.22 |
| 203 | E866 $\sigma_{pd}/(2\sigma_{pp})$ | 15 | 1.24 | 0.80 | 0.43 |
| 245+250 | LHCb 7TeV& 8TeV $W,Z$ | 29+30 | 1.15 | 1.17 | 1.44 |
| 246 | LHCb 8TeV $Z \to ee$ | 17 | 1.35 | 1.43 | 1.57 |
| 248 | ATLAS 7TeV $W,Z$(2016) | 34 | 1.96 | 1.79 | 2.33 |
| 260 | D0 Z rapidity | 28 | 0.56 | 0.58 | 0.62 |
| 267 | CMS 7TeV eletron $A_{ch}$ | 11 | 1.47 | 1.52 | 0.76 |
| 269 | ATLAS 7TeV $W,Z$(2011) | 30 | 1.03 | 0.93 | 1.01 |
| 545 | CMS 8TeV incl. jet | $185/174^{\dagger\dagger}$ | 1.03 | 1.39 | 1.30 |
| Total | $N_{pt}$ | — | 2263 | 1991 | 2256 |
| Total | $\chi^2/N_{pt}$ | — | 1.14 | 1.15 | 1.20 |

- Similar overall quality of fit in $\chi^2/N$.
- Differences remaining in some datasets:
  - NuTeV agreement improved but difference remains, seen in $s + \bar{s}$.
  - Some differences in NNPDF fit quality to small datasets, e.g. CMS 7 TeV electron asymmetry.

Table from T. Hobbs

# High $x$ gluon - Jet tensions

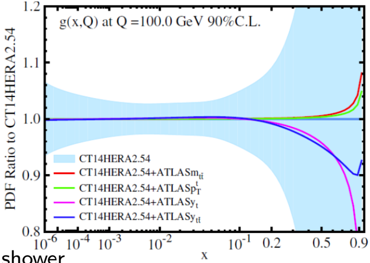
- Not only tensions between different dataset types at high $x$, also tensions within dataset types, e.g. between different jet measurements.
- ATLAS 7 TeV jets pulls gluon down at high $x$, whereas CMS jets (mainly 8 TeV) pull gluon up.
- Global fit is a balance between these different pulls and those of $Zp_T$, $t\bar{t}$ datasets here.




† MSHT20, TC, S. Bailey, L. Harland-Lang, A. Martin, R. Thorne 2012.04684

# ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets

- MSHT*, find difficulties fitting all 4 distributions - $m_{tt}, y_t, y_{tt}, p_t^T$ - simultaneously. CT find same and fit only $p_t^T$ and $m_{tt}$ together.
- MSHT, CT$^+$, ATLAS$^-$ cannot get good fit to $y_t$ or $y_{tt}$ individually.
- NNPDF however able to fit all 4 distributions well individually $^\dagger$.
- Different pulls observed for $m_{tt}, p_t^T$ relative to $y_t, y_{tt}$:
- CT, MSHT decorrelate parton shower systematic to obtain reasonable fit to $p_t^T$ and $m_{tt}$ for former or all 4 for latter:




Plot from C.-P. Yuan

| | |
|---|---|
| $p_T$ | 0.53 |
| $y_t$ | 3.12 |
| $y_{tt}$ | 3.51 |
| $M_{tt}$ | 0.70 |
| $p_T + M_{tt}$ | 5.73 |
| Combined | 7.00 |

Decorrelate parton shower (within and between)

| Distribution | p.s. correlated | p.s. decorrelated |
|---|---|---|
| Combined | 7.00 | 1.80 |
| $p_\perp^t + M_{tt}$ | 5.73 | 0.66 |

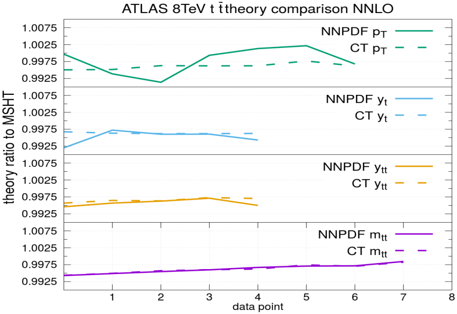
* S. Bailey & L.Harland-Lang 1909.10541.
† Czakon et al 1611.08609.
+ Kadir et al 2003.13740.
− ATL-PHYS-PUB-2018-017.

# Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

- Start by adding this to the reduced fit, first check theory predictions for PDF4LHC15 read in (no fitting).
- Differences noted in data treatment due to shifting (MSHT) to centre of asymmetric errors, differences in theory due to inclusion (MSHT) or not (CT,NNPDF) of EW corrections.
- Upon removal of these differences, data agree and theory agrees to better than 1%.
- All groups $\chi^2$ in agreement and follow same pattern:

| Distribution/N | MSHT | CT | NNPDF |
|---|---|---|---|
| $p_t^T/8$ | 3.0 | 3.1 | 3.4 |
| $y_t/5$ | 10.6 | 10.1 | 9.5 |
| $y_{tt}/5$ | 17.6 | 15.3 | 16.2 |
| $m_{tt}/7$ | 4.3 | 4.2 | 4.1 |

- Differences in global fits likely not from $t\bar{t}$ theory implementations.



# ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets

- Comes differential in 4 variables with statistical and systematic correlations - $m_{tt}, y_t, y_{tt}, p_t^T$.
- MSHT*, CT+ difficulties fitting all 4 distributions simultaneously.
- MSHT, CT, ATLAS− cannot get good fit to $y_t$ or $y_{tt}$ individually.
- NNPDF3.0 however able to fit all 4 distributions well individually†.

Benchmarking:

- Start by adding this to the reduced fit, first check theory predictions for PDF4LHC15 read in (no fitting):
  - Data agree and theory agrees to better than 1%.
  - All groups $\chi^2$ in agreement and follow same pattern:

| Distribution/N | MSHT | CT | NNPDF |
|---|---|---|---|
| $p_t^T/8$ | 3.0 | 3.1 | 3.4 |
| $y_t/5$ | 10.6 | 10.1 | 9.5 |
| $y_{tt}/5$ | 17.6 | 15.3 | 16.2 |
| $m_{tt}/7$ | 4.3 | 4.2 | 4.1 |

  - Differences in global fits likely not from $t\bar{t}$ theory implementations.

* S. Bailey & L.Harland-Lang 1909.10541.
† Czakon et al 1611.08609.
+ Kadir et al 2003.13740.
− ATL-PHYS-PUB-2018-017.

# Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

- *What happens when this dataset is added to the reduced fits?*
- Two cases considered - "uncorrelated" (all systematic and statistical correlations between distributions turned off) and "correlated" (including all correlations, produces a very poor fit):

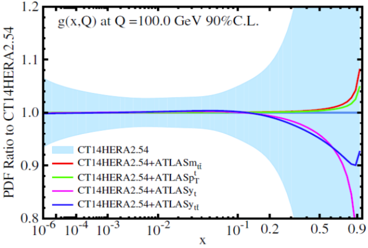
| Distribution/N | $p_t^T/8$ | $y_t/5$ | $y_{tt}/5$ | $m_{tt}/7$ | Total |
|---|---|---|---|---|---|
| MSHT uncorrelated | 3.8 | 8.4 | 12.5 | 6.4 | 31.2 |
| NNPDF uncorrelated | 7.2 | 3.9 | 5.1 | 2.5 | 18.7 |
| CT uncorrelated | 3.4 | 12.9 | 17.3 | 6.1 | 39.7 |
| MSHT correlated | - | - | - | - | 130.6 |
| NNPDF correlated | - | - | - | - | 122.7 |
| MSHT decorrelated | - | - | - | - | 35.3 |

- MSHT observe usual pattern as in global fits, $p_t^T$ and $m_{tt}$ can be fit but $y_t$, $y_{tt}$ struggle, although better than in full fit. Awful fit if all correlations included, can fit with parton shower decorrelation.
- CT see usual global fit pattern also, poor fits to rapidities $y_t$, $y_{tt}$.
- NNPDF however able to fit rapidity distributions in uncorrelated case, yet correlated case similar to MSHT.

# Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

Preliminary!

- Potential explanation division of training and validation in NNPDF.
- Training fraction usually 50%, for small datasets this is unfeasible - all data in training.
- Potentially double-weights small datasets - e.g. ATLAS $t\bar{t}$.
- Affects balance of $p_t^T$, $m_{tt}$ and $y_t$, $y_{tt}$, which have some tension.




| Dataset | MSHT uncorrelated | NNPDF uncorrelated | MSHT uncorrelated double weight |
|---|---|---|---|
| Total | 2314.1 | 2731.4 | 2313.3 |
| $\chi^2/N$ | 1.15 | 1.20 | 1.15 |
| DYratio (15) | 9.5 | 5.2 | 9.2 |
| CMS $W$ asym. (11) | 14.2 | 8.2 | 10.2 |
| $p_t^T$ (8) | 3.8 | 7.2 | 4.2 |
| $y_t$ (5) | 8.4 | 4.3 | 5.8 |
| $y_{tt}$ (5) | 12.5 | 5.7 | 7.4 |
| $m_{tt}$ (7) | 6.4 | 2.4 | 6.5 |
| $t\bar{t}$ total | 31.2 | 19.6 | 23.9 |

- May also explain NNPDF better fit of E866 DYratio data and CMS $W$ charge asymmetry data (15 and 11 points respectively):

# Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

Preliminary!

- Additional explanations are other datasets included - tensions?
- NNPDF-3.0 had little jet data. NNPDF-4.0 will have much more, it sees similar issues as MSHT, CT, ATLAS for this dataset.
- Useful to consider different jet datasets as well as CMS 8 TeV jets*:

| Dataset (N) | MSHT reduced (default CMS8j) | MSHT reduced + CMS7j | MSHT reduced + AT7j | MSHT reduced (CMS7j only) | MSHT reduced (AT7j only) | MSHT reduced (no jets) |
|---|---|---|---|---|---|---|
| $\chi^2/N$ | 1.15 | 1.15 | 1.18 | 1.11 | 1.17 | 1.12 |
| CMS 8 TeV jets (174) | 243.6 | 247.2 | 249.9 | - | - | - |
| CMS 7 TeV jets (158) | - | 163.5 | - | 156.4 | - | - |
| ATLAS 7 TeV jets (140) | - | - | 225.7 | - | 210.4 | - |
| $p_t^T$ (8) | 3.8 | 4.0 | 4.3 | 4.0 | 4.6 | 4.5 |
| $y_t$ (5) | 8.4 | 7.3 | 7.3 | 6.4 | 5.5 | 5.2 |
| $y_{tt}$ (5) | 12.5 | 9.8 | 10.2 | 7.2 | 5.2 | 6.6 |
| $m_{tt}$ (7) | 6.4 | 6.4 | 7.0 | 6.4 | 6.4 | 7.4 |
| $t\bar{t}$ total | 31.2 | 27.5 | 28.8 | 24.0 | 21.6 | 23.8 |

- Tensions between CMS 8 TeV jets and ATLAS, CMS 7 TeV jets.
- Similar tensions with ATLAS 8 TeV $t\bar{t}$, specifically the rapidity distributions, which favour lower gluon.

*Note "uncorr" case shown, systematic correlations not included, same pattern observed in "corr" case.

# ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets: MSHT20*

- MSHT observe the rapidity $y_t$ and $y_{tt}$ distributions have very poor fit quality even when fit alone.
- Moreover, fitting the $p_t^T$ and $m_{tt}$ together or all 4 datasets combined results also in a very poor fit:

| | |
|---|---|
| $p_T$ | 0.53 |
| $y_t$ | 3.12 |
| $y_{tt}$ | 3.51 |
| $M_{tt}$ | 0.70 |
| $p_T + M_{tt}$ | 5.73 |
| Combined | 7.00 |

Decorrelate parton shower

(within and between) →

| Distribution | p.s. correlated | p.s. decorrelated |
|---|---|---|
| Combined | 7.00 | 1.80 |
| $p_\perp^t + M_{tt}$ | 5.73 | 0.66 |

- Tensions exists between shifts required for large systematics of the different distributions, particularly parton shower uncertainty (and ISR/FSR and hard scattering systematics).
- Two-point systematic evaluated using 2 Monte Carlo generators, assuming any correlation factor determined applies fully correlated way across all bins and distributions is a strong assumption.

* S. Bailey & L.Harland-Lang 1909.10541 and MSHT20 2012.04684.

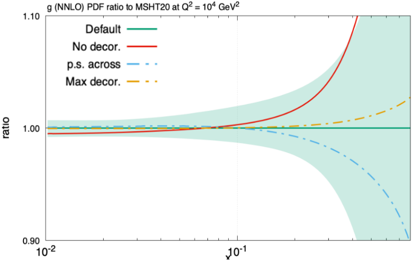
# ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets: MSHT20*

- Assumption of full correlation of parton shower systematic can be relaxed, then a reasonable fit is possible.
- CT decorrelate this systematic between distributions and fit the $p_t^T$ and $m_{tt}$ combination only by default †.
- MSHT do this decorrelation between all 4 distributions and also split it into 2 sources varying smoothly within each distribution:

$$\beta_i^{(1)} = \cos\left[\pi\left(\frac{y_{tt,i} - y_{tt,\min}}{y_{tt,\max} - y_{tt,\min}}\right)\right]\beta_i^{\text{tot}}, \qquad \beta_i^{(2)} = \sin\left[\pi\left(\frac{y_{tt,i} - y_{tt,\min}}{y_{tt,\max} - y_{tt,\min}}\right)\right]\beta_i^{\text{tot}}.$$

- Then a reasonable fit is possible, e.g. in MSHT20:

| Baseline | No decor. | parton shower across | Max decor. |
|---|---|---|---|
| 1.04 | 6.84 | 1.69 | 0.81 |

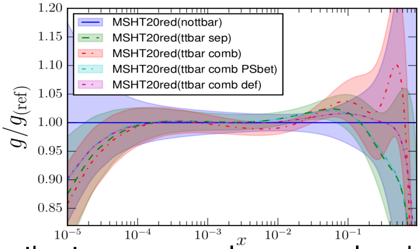



* S. Bailey & L.Harland-Lang 1909.10541 and MSHT20 2012.04684.

† T.-J. Hou et al, CT18 1912.10053.

# ATLAS 8 TeV multi-differential $t\bar{t}$ lepton+jets Preliminary!

- What effect does the inclusion of this data in the reduced fit have on the gluon?

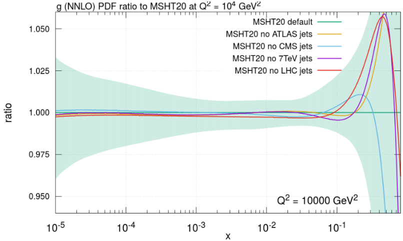



- Fitting all 4 distributions separately, uncorrelated ⇒ gluon moves down at high $x$, driven by the rapidity data.
- Applying correlations ⇒ gluon raised and shape altered at high $x$ .
- Decorrelating parton shower between distributions ⇒ reverts the gluon to shape obtained when all 4 separately uncorrelated fitted.
- Additionally decorrelating within distributions ⇒ moves gluon closer to fit without $t\bar{t}$ data as its constraining power is reduced.
- Overall, gluon shape moves in direction of global fit gluon.

# Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

- Additional explanations are other datasets included - tensions?
- Tensions exist within and between different dataset types at high $x$.

- ATLAS 7 TeV jets favour lower gluon at high $x$, whereas CMS 8 TeV jets pull gluon up.
- ATLAS 8 TeV $t\bar{t}$ data pull gluon down.
- Global fit is a balance between these different pulls.




† MSHT20, TC, S. Bailey, L. Harland-Lang, A. Martin, R. Thorne, 2012.04684

- Tensions may be part of reason this dataset, and particularly the rapidities, is poorly fit. So far only included CMS 8 TeV jet dat.
- *Could this also be affecting the ATLAS 8 TeV $t\bar{t}$ lepton+jets in the reduced fits and the global fits?*

# Benchmarking ATLAS 8 TeV $t\bar{t}$ lepton+jets

Very Preliminary!

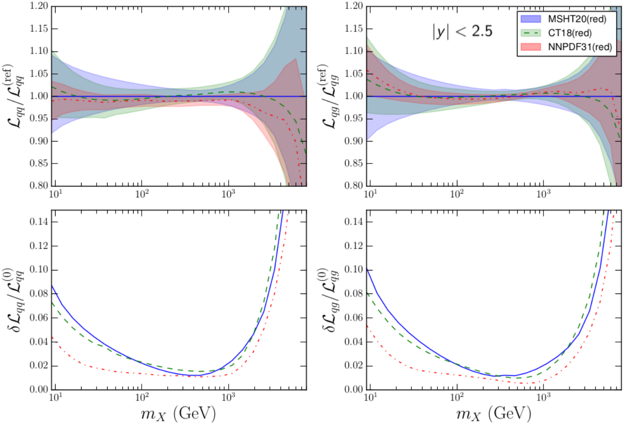
- Additional explanations are other datasets included - tensions?
- NNPDF-3.0 had little jet data. NNPDF-4.0 will have much more, it sees similar issues as MSHT, CT, ATLAS for this dataset.
- Useful to consider different jet datasets as well as CMS 8 TeV jets*:

| Dataset (N) | MSHT reduced (default CMS8j) | MSHT reduced + CMS7j | MSHT reduced + AT7j | MSHT reduced (CMS7j only) | MSHT reduced (AT7j only) | MSHT reduced (no jets) |
|---|---|---|---|---|---|---|
| $\chi^2/N$ | 1.14 | 1.14 | 1.17 | 1.17 | 1.16 | 1.12 |
| CMS 8 TeV jets (174) | 240.4 | 246.9 | 251.6 | - | - | - |
| CMS 7 TeV jets (158) | - | 167.8 | - | 168.0 | - | - |
| ATLAS 7 TeV jets (140) | - | - | 228.9 | - | 212.7 | - |
| $t\bar{t}$ total | 27.6 | 25.2 | 23.1 | 21.7 | 19.5 | 25.6 |

- Tensions between CMS 8 TeV jets and ATLAS, CMS 7 TeV jets.
- Similar tensions with ATLAS 8 TeV $t\bar{t}$, specifically the rapidity distributions, which favour lower gluon.
- Same tensions observed without correlations or with MSHT default treatment.

*Note MSHT20 default treatment of systematic correlations shown, decorrelates PS between and within distributions.

# Reduced Fits: Current Status Summary*




- Very good agreement in the gluon-gluon, quark-quark and quark-gluon luminosities.
- Small difference in quark-antiquark luminosity, still some flavour decomposition differences, although within MSHT uncertainties.

*Note this is without the $t\bar{t}$ added.

# PDF4LHC21 Benchmarking Summary:

- Great amounts of new data, theoretical improvements, PDF methodological improvements have meant substantial changes since PDF4LHC15.
- We have been performing a benchmarking exercise of the 3 global fit PDF groups most recent sets: MSHT20, CT18, NNPDF3.1.
- Based on comparing "Reduced Fits" with common dataset and common theory settings where possible.
- Goal of exercise is the understanding of differences which have emerged in PDF central values and uncertainties.
  $\Rightarrow$ Good progress.
- End result: PDF4LHC21 set of PDFs, central PDFs and Hessian error set (30-50 sufficient) representing the 3 published PDFs.
- We welcome suggestions, feedback and discussion!

More details on all of this in the slides!